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Mind off driving:
Effects of cognitive load on driver glance behaviour and
response times

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Gothenburg, Sweden 2018

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Abstract

Introduction: Safe driving requires drivers to look at relevant information in the traffic environment and react in time in case a critical event arises. Concerns exist that cognitively loading tasks might interfere with drivers' abilities to do this. Studies on the effects of cognitive tasks on driver behaviours are however ambiguous and incomplete. The recently formulated cognitive control hypothesis might be able to explain some of the inconsistencies. **Objectives:** The aim of this thesis is to better understand the effect of cognitive tasks on response times in unexpected lead vehicle braking scenarios and on glance behaviour in traffic environments with potential threats in off-path locations. Effects are studied both at aggregated levels and with higher temporal resolution. **Method:** A series of experiments were conducted in an advanced driving simulator. **Results:** Cognitive tasks increased response times in the non-automated, artificial Detection Response Task (DRT) but did not influence response times in an unexpected lead vehicle braking scenario. Also, drivers adapted their visual scanning behaviour to the traffic environment in the same way in terms of timing when doing cognitive tasks as when not, but to a lesser degree. Interestingly, the effect of cognitive load on the visual behaviour depended on gaze direction and the demand variations in the cognitive task. **Conclusions:** The results demonstrate the importance of context when trying to interpret effects of cognitive load on traffic safety and are in line with the cognitive control hypothesis. They also indicate that there is not a unidirectional and uniform effect of cognitive activities on driver behaviour. This calls for further exploration of the interaction between the cognitive task and the driving task.

Keywords: cognitive load, distraction, driver behaviour, traffic safety, visual behaviour, response times, intersections, lead vehicle braking

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I. Background

Car drivers do more behind the wheels than just driving. Analyses of naturalistic driving data and video recordings of car drivers shown that drivers are visibly engaged in some secondary activity (e.g. adjusting the radio, eating, or conversing on a cell phone) 23.5 % of the driving time (Klauer, Guo, Sudweeks, & Dingus, 2010). In addition to this visible engagement, drivers may also be engaged in activities which are not visible on camera, such as thinking, active listening and mind wandering. While there is a convincing amount of research from both controlled driving experiments and naturalistic studies showing an increased risk of crashes and near-crashes due to visual distraction (i.e. when drivers takes their eyes off the forward roadway; Angell et al., 2006; Caird, Johnston, Willness, Asbridge, & Steel, 2014; Dingus et al., 2016; Drews, Yazdani, Godfrey, Cooper, & Strayer, 2009; Fitch et al., 2013; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006; Olson, Hanowski, Hickman, & Bocanegra, 2009; Victor et al., 2015), the effect on driver performance and traffic safety from non-visual, cognitively loading activities unrelated to the task of driving is less clear. From here on, I will refer to such activities as cognitive activities. Tasks which require cognitive activity will be referred to as cognitive tasks. Although mind wandering can also be considered a type of cognitive activity, this thesis focuses on cognitive activities in the form of secondary tasks and does thus not included mind wandering in these concepts. Cognitive load will be considered the amount of cognitive resources used at a certain time, and cognitive resources in turn refer to the neural mechanisms necessary for cognitive control (which can also be referred to as supervisory control or executive attention; Engström, Monk et al., 2013).

The topic is highly relevant due to the technical development which has enabled voice-based auditory interfaces in in-vehicle and portable devices, as well as the common use of cell phones for conversing while driving. The National Highway Traffic Safety Administration (NHTSA), part of the U.S. Department of Transportation, are currently working on guidelines for such in-vehicle and portable devices with auditory-vocal interfaces, intended to minimize the negative effects from the devices on traffic safety (U.S. Department of Transportation, National Highway Traffic Safety Administration, 2013). Research which can be informative of risks and benefits with such devices are thus needed.

Strong concerns have been raised regarding negative effects from cognitive activities on traffic safety (Caird, Willness, Steel, & Scialfa, 2008; Recarte & Nunes, 2003; Strayer, Cooper, Turrill, Coleman, & Hopman, 2015; Strayer, Turrill et al., 2015). The concerns are based on numerous studies which have found increased response times, deteriorated visual scanning and impaired processing of information during execution of cognitive tasks in controlled driving experiments. These effects are assumed to generalize to real life driving and therefore (implicitly or explicitly) predict slower responses in critical situations and an increased risk of missing relevant information in the traffic environment.

Naturalistic studies, however, typically don't find an increased crash or near crash risk during cognitive tasks, such as cell phone conversations or the use of Citizens Band (CB) radio (Fitch et al., 2013; Hickman, Hanowski, & Bocanegra, 2010; Klauer et al., 2006; Olson et al., 2009; Victor et al., 2015). Some have even found a decreased crash and near crash risk during such tasks (Hickman et al., 2010; Olson et al., 2009; Victor et al., 2015). This makes other researchers question the conclusions drawn from controlled experiments. Several plausible explanations have been suggested for the seemingly inconsistent results found in controlled experiments and naturalistic studies. For example that controlled studies suffer an "observer effect" (drivers that are aware of being watched alter their behaviour; Young, 2015), that the control or baseline conditions in controlled experiments are most likely different from those in naturalistic studies (Fisher, 2015), and that while controlled experiments typically study maximal performance this is not typical driver behaviour (Hancock & Sawyer, 2015; Shinar, 2015). Also, in real life situations cognitive activities might have a positive effect on under-load (Hancock & Sawyer, 2015) and drivers can adapt risk compensating strategies such as longer following times when engaging in cognitive activities (Young, 2015).

While actual crash risks can only be estimated from naturalistic studies, researchers have no control over the level of cognitive load in such studies. Also, because crashes are rare events, large amounts of data has to be collected and statistical analyses can only be made on rather broadly defined crash scenarios. Controlled experiments, despite their limitations discussed earlier, are therefore important since they allow for repeatable scenarios and a higher level of control of the cognitive load by employment of cognitive tasks.

2. Effects of cognitive tasks on driving

Driving is a complex task in which the driver has to make notice of and act on things in the constantly changing environment. As previously mentioned, concerns have been raised that cognitive activities might increase car drivers' response times, deteriorate their visual scanning and impair processing of information. Although all these abilities are crucial for safe driving, focus here will be on the first two, as these can be measured in observable behaviours.

2.1. Response times during cognitive activities

There is a great concern that cognitive activities would lead to increased response times in critical situations, resulting in an increased risk of accidents (Caird et al., 2008; Merat & Jamson, 2008; Patten, Kircher, Östlund, & Nilsson, 2004; Strayer & Fisher, 2016; Strayer, Turrill et al., 2015). The concern is based on the large amount of experiments that has shown increased response times to different stimuli, such as artificial detection tasks (Bruyas & Dumont, 2013; Conti, Dlugosch, Vilimek, Keinath, & Bengler, 2012; Engström, Larsson, & Larsson, 2013; Harbluk, Burns, Hernandez, Tam, & Glazduri, 2013; Mantzke & Keinath, 2015; Merat & Jamson, 2008; Patten et al., 2004) as well as braking lead vehicles (Alm & Nilsson, 1995; Engström, Aust, & Viström, 2010; Lee, Caven, Haake, & Brown, 2001; Salvucci & Beltowska, 2008; Strayer et al., 2013; Strayer, Drews, & Johnston, 2003), when drivers have performed cognitive tasks. However, naturalistic data has, as previously mentioned, shown a decreased risk of rear-end collisions during cell phone conversations (Victor et al., 2015), something that appears peculiar if one assumes increased response times to braking lead vehicles.

In a meta-study by Engström (2010) it was shown that the experimental design itself had a large effect on the effect size of cognitive activities on brake response times in lead vehicle braking scenarios. More specifically, the effect size was found to be dependent on the initial time headway (THW) to the lead vehicle (the headway at the moment of lead vehicle braking), that is, the scenario criticality. In studies where the initial THW was large, cognitive activities had a large effect on the response time, while in studies where the THW was small, cognitive tasks had a much smaller effect on the response time. Interestingly, it has been found in naturalistic data that response times in rear-end crashes and near-crashes also depend on the scenario criticality (Markkula, Engström, Lodin, Bärgman, & Victor, 2016). The level of cognitive load is however unknown.

Recently, Engström, Markkula, Victor, & Merat (2017) formulated the cognitive control hypothesis, a theoretical framework that appears helpful in order to understand the seemingly inconsistent effects of cognitive tasks on response times.

2.1.1. The cognitive control hypothesis

The cognitive control hypothesis suggests that *cognitive load selectively impairs driving subtasks that rely on cognitive control but leaves automatic performance unaffected* (Engström et al., 2017). Automatic behaviours are effortless and don't require active control or attention by the subject, while the opposite is true for controlled behaviours (Schneider & Shiffrin, 1977). Engström et al. (2017) propose that the Guided Activation Theory (GAT) provides a useful model for explaining the relationship between controlled and automatic behaviours and how automaticity develops. The GAT model describes in neurobiological terms how all behaviours (responses to stimuli) lie somewhere on a continuum between controlled and automatic, where the degree of automaticity is determined by neural pathway strength (Botvinick & Cohen, 2014; Cohen, Dunbar, & McClelland, 1990; Miller & Cohen, 2001). Successful employment of neural pathways increases their strength and lead to a higher degree of automaticity (Cohen et al., 1990). This means that tasks with a consistent stimulus-response mapping can become automatized through extensive practice.

To successfully deal with novel or inconsistent tasks, flexible and non-routine behaviours are necessary. This often requires overriding strong pathways in favour of activating weaker ones that have higher relevance for resolving the novel task(s). This is achieved through the employment of cognitive control, which is subsumed primarily by the frontal cortex (Botvinick & Cohen, 2014; Miller & Cohen, 2001). If a behaviour with weak pathway strength is not activated through cognitive control, stronger pathways will instead activate, resulting in routine, or automatic, behaviour.

In a driving context, this means that when drivers encounter new or inconsistent situations, such as when driving through a busy, non-signalized intersection, they need to apply cognitive control in order to adapt their behaviour to fit the current situation. However, applying cognitive control requires effort and drivers will only do so to the extent they believe it is worth the cost. That is, their behaviour is typically satisficing, rather than optimizing (Summala, 2007). Also, during cognitive activities the driver has less cognitive resources available and is hence less capable of applying

cognitive control to driving. The driving thus comes to depend more on automatized behaviours (Engström, Victor, & Markkula, 2013; Engström et al., 2017).

When interpreting the previously mentioned response time studies from the cognitive control hypothesis perspective, one has to consider whether or not the employed stimuli elicits automatic responses. Tasks that are novel to the participants are not expected to elicit automatic responses due to insufficient stimulus-response mapping. The hypothesis thus predicts increased response times when doing cognitive tasks in those cases. One such task which is frequently used is the ISO standardized Detection Response Task, DRT (ISO, 2016). DRT requires participants to press a button as fast as possible upon detection of a visual or tactile stimulus presented at irregular intervals of 3-5 s. Although practiced before trials, it is not practiced to the extent that full automaticity can be expected (Shiffrin & Schneider, 1977; ISO, 2016). In line with the hypothesis' prediction, numerous studies have shown increased response times to the DRT stimulus during cognitive task execution compared to a baseline (no task) condition (Bruyas & Dumont, 2013; Conti et al., 2012; Engström, Larsson et al., 2013; Harbluk et al., 2013; Mantzke & Keinath, 2015; Merat & Jamson, 2008; Patten et al., 2004; Törnros & Bolling, 2005).

In lead vehicle braking studies, it is necessary to take into account what the drivers are responding to (what the stimulus is) in order to assess the degree of automaticity. Potential stimuli are brake lights and visual looming of the lead vehicle (the optical expansion of the lead vehicle on the driver's retina). Looming objects on collision course with the subject unconsciously capture attention (Lin, Franconeri, & Enns, 2008) and elicit automatic avoidance responses in humans (Náñez, 1988) as well as other species (Oliva, Medan, & Tomsic, 2007; Schiff, Caviness, & Gibson, 1962). The cognitive control hypothesis thus predicts non-interference with brake responses from cognitive activities in the case of a looming lead vehicle. Brake lights on the other hand are not likely to elicit automatic responses, based on their inconsistent association with the immediate need to brake in every day driving. That is, brake lights are often encountered in situations which do not require an immediate brake response and are thus not consistently mapped to a brake response. Therefore, the cognitive control hypothesis predicts interference (longer response times) from cognitive activities on responses to brake light onset, provided that visible looming is absent.

Cognitive control can also be employed in order to improve response times in studies where the lead vehicle braking is anticipated, either due to instructions, cues in the traffic environment or scenario repetition (again, provided that visible looming is absent). Response times in studies with such designs are hence also expected to be affected by cognitive tasks.

Results from existing lead vehicle braking studies are in line with those predictions. The vast majority of the studies have employed study designs which allows for or requires employment of cognitive control (Alm & Nilsson, 1995; Engström et al., 2010; Lee et al., 2001; Salvucci & Beltowska, 2008; Strayer et al., 2013, 2003). An exception is Muttart, Fisher, Knodler, & Pollatsek (2007), who studied response times in a lead vehicle braking scenario which could either be predicted using downstream traffic events, or only by the looming of the slowing lead vehicle. In line with the hypothesis, they found no effect of cognitive task execution on the response distance in the un-cued (looming only) condition, whereas in the cued condition cognitive distraction significantly increased the response distance. Similarly Baumann, Petzoldt, Groenewoud, Hogema, & Krems (2008) found that cognitive task execution caused a reduction in time to collision (TTC) at throttle release when there was an obstacle after a curve that had been cued by a warning sign, but not when the sign was absent and the response was solely triggered by the looming obstacle.

In sum, the seemingly inconsistent effects of cognitive tasks on response times appears to be well explained by the cognitive control hypothesis (Engström et al., 2017). That is, response times in tasks and scenarios where cognitive control is employed when generating the response, such as in novel or inconsistent tasks and anticipated events, are increased by cognitive activities. Responses which are automatically triggered, for example by visual looming, are however not prolonged, although little research has been done with such study designs.

2.2. Visual behaviour during cognitive activities

Car drivers' most common gaze direction is towards the future path (Ahlström, Victor, Wege, & Steinmetz, 2012; Harbluk, Noy, Trbovich, & Eizenman, 2007; Victor, Harbluk, & Engström, 2005; Wang, Reimer, Dobres, & Mehler, 2014). When cognitively loaded, drivers increase the time spent looking towards the future path even more (Harbluk et al., 2007; Reimer, Mehler, Dobres, & Coughlin, 2013; Wang et al., 2014) and show a greater gaze concentration (i.e. reduced gaze variability; Recarte & Nunes, 2000,

2003; Reimer, Mehler, Wang, & Coughlin, 2012; Reimer, 2009; Victor et al., 2005; Wang et al., 2014). Looking at the future path is important for lane keeping and path planning, as well as for noticing objects on an immediate collision course. The altered visual behaviour under cognitive load has therefore been suggested to reflect a prioritization of the most safety relevant area (Recarte & Nunes, 2000, 2003) and could perhaps help explain why drivers conversing on a cell phone have been found to have a decreased risk of rear-end collisions (Victor et al., 2015). Others have argued that it reflects a disrupted scanning for potential hazards (Strayer, Turrill et al., 2015) and therefore can delay driver actions (Harbluk et al., 2007).

Most studies of drivers' visual behaviour are done on highways or main roads where the visual behaviour is studied over longer periods of time (Recarte & Nunes, 2000, 2003; Reimer et al., 2012; Reimer, 2009; Victor et al., 2005; Wang et al., 2014). Such settings do not require many off-path glances (glances to other locations than the future path, the on-path). The implications of an increased amount of glances towards the future path in such environments is thus most likely different from environments with larger amounts of relevant information in off-path locations, such as intersections. Also, such aggregated effects of altered visual behaviours are not informative regarding the coupling between off-path glances and relevant visual information at off-path locations.

A few studies have demonstrated a decreased number of glances also towards relevant visual information in off-path locations. In a study in city traffic by Harbluk et al. (2007), drivers doing cognitive tasks had fewer glances towards traffic lights and towards the right at intersections. Similarly, Strayer, Turrill et al. (2015) found that cognitive tasks caused drivers to make fewer scans to the right and left in critical locations (e.g. intersections) in suburban driving. Lehtonen, Lappi, & Summala (2012) found that drivers had fewer glances towards the occlusion point in curve driving (the point where the road disappears behind e.g. vegetation and where oncoming traffic can hence first be spotted) when doing a cognitive task, and Muttart et al. (2007) found that drivers had fewer glances in rear view mirrors before lane changes in simulated construction zones.

The timing of drivers' glances in relation to situationally relevant places in the environment remains to be explored.

While the effects of cognitive activities on driving behaviour have been the focus of significant research, there are still key areas which need to be

investigated further. In particular, drivers' response times in unexpected situations with visible looming, and their visual scanning behaviour in relation to relevant information in off-path locations.

3. Objectives

The overall aim of this PhD project is to increase the understanding of how cognitive activities affect car driver's abilities and behaviours from a traffic safety perspective. The effects of cognitive activities will be studied as aggregated effects in various contexts, which is in line with most previous work in the area, but also at a more detailed level that employs a higher temporal resolution. That is, the time course of the effects and the interaction between cognitive tasks, traffic environment and driver behaviour will be explored.

The present licentiate thesis includes the first steps to achieve the overall aim and has the following research questions:

- Does cognitive load affect drivers' response times in an unexpected, critical lead vehicle braking scenario in the same way as in the artificial Detection Response Task (DRT)?
- Are the general effects of cognitive load on drivers' visual behaviour found on highways and main roads similar in traffic scenarios with relevant visual information in off-path locations, namely intersections and hidden exits?
- How does the time course of driver visual behaviour respond to a cognitive task and to relevant information in off-path locations in the traffic environment?

The approach taken in this licentiate work was to explore driver behaviours and responses through driving simulator experiments and the employment of a well-established cognitive task. This was to allow for a high level of experimental control. To improve the ecological validity the experiments were carried out in an advanced moving base simulator and effort was put into making the driving task as realistic as possible.

4. Summary of papers

The papers included in this thesis are:

Paper I

Nilsson, E., Ljung Aust, M., Engström, J., Svanberg, B. and Lindén, P. (2018). *Effects of cognitive load on response time in an unexpected lead vehicle braking scenario and the Detection Response Task (DRT)*. Manuscript submitted for publication.

Paper II

Nilsson, E., Victor, T., Ljung Aust, M., Svanberg, B., Lindén P. and Gustafsson, P. (2018). *Car drivers' glance behaviour towards potential threats during cognitive tasks: The time course of cognitive load effects*. To be submitted.

Paper I. Effects of Cognitive Load on Response Time in an Unexpected Lead Vehicle Braking Scenario and the Detection Response Task (DRT)

Introduction

Many experimental studies have demonstrated increased response times to various stimuli during cognitive activities. This has led to concerns that cognitive activities will increase response times also in critical situations in real life driving. A commonly used response time task which consistently show increased response times during cognitive activities is the ISO standardized Detection Response Task (DRT). However, a few studies have been made where the driver's response is triggered solely by visual looming and where no effect of cognitive activities on response times has been found.

Aim

The aim of this paper was to see if the same cognitive task had similar effects on response times in the DRT as in an unexpected lead vehicle braking scenario with strong visual looming.

Method

The study consisted of two experiments. In experiment 1, 16 participants drove a fixed-base driving simulator on a four lane highway in approximately 90 km/h. Besides just driving (baseline), they performed an audio version of the cognitively loading n-back task at two levels of difficulty, 1-back and 2-back. This was done with and without concurrent execution of the tactile DRT.

In experiment 2, 24 participants drove a moving-base driving simulator on a two lane rural road in approximately 80 km/h. After approximately 40 minutes of driving, the participant's vehicle was overtaken by another car, which after overtaking suddenly braked in front of the participant. The scenario was designed so that visual looming appeared as soon as the overtaking car started braking. The participants were either just driving, or involved in the 1-back or 2-back task when the overtaking car started braking.

Results

In experiment 1, the cognitive tasks caused an increase in the DRT response times. In experiment 2, there was no effect of the same cognitive tasks on throttle release or brake response times.

Discussion

The same cognitive tasks did not have similar effects on response times in the DRT as in an unexpected lead vehicle braking scenario. This can potentially be explained by the cognitive control hypothesis (Engström et al., 2017). The cognitive control hypothesis says that *cognitive load selectively impairs driving subtasks that rely on cognitive control but leaves automatic performance unaffected*. Since the DRT is a relatively novel task for the participants, it requires cognitive control and DRT performance is hence negatively affected by cognitive tasks, according to the hypothesis. Responses to visual looming are however innate and automatic and should, according to the hypothesis, not be affected by cognitive tasks. The results suggest that it is inappropriate to generalize effects of cognitive tasks seen in cognitively controlled response tasks, such as the DRT, to critical situations where drivers can respond to visual looming.

Paper II. Car drivers' glance behaviour towards potential threats during cognitive tasks: The time course of cognitive load effects

Introduction

Visual information from the traffic environment is necessary for safe driving. Numerous studies on highways and other larger roads have found a gaze concentration effect with more on-road glances during cognitive task execution. Less research has focused on the effects of cognitive tasks on drivers' visual adaptation to traffic scenarios with relevant information in off-path locations. Further, the time course of the visual behaviour alterations had not been explored.

Aim

The aim of this paper was to study how cognitive tasks affected car drivers' visual behaviour in two traffic scenarios with potential threats in off-path locations. The time course of the drivers' visual behaviour was to be studied both in relation to the traffic environments and the cognitive tasks.

Method

Thirty-six participants drove on a rural road in a moving-base driving simulator. Two scenarios, an intersection scenario and a hidden exit scenario, were repeated four times each during the 40 minutes long drive. The scenarios were designed such that they contained potential threats in off-path locations, but that no situations that required driver responses evolved. When passing the scenarios, the participants were either engaged in a cognitive task (the 1-back or 2-back task), or were just driving. The drivers' glance behaviour when driving through the scenarios was recorded using an eye-tracker.

Results

The drivers adapted their visual behaviour to the traffic scenarios by decreasing the number of on-path fixations and directing their gaze towards relevant information in off-path locations. When cognitively loaded, the proportion of on-path fixations increased but the timing of the glances towards the off-path locations was unaffected.

Cognitive load was found to affect on-path and off-path fixations and glances differently. The duration of on-path fixations increased under load, while no such effect was found in off-path fixations. Also, a "gaze freezing"

effect was found if the gaze direction was on-path when the demand from the cognitive tasks increased (i.e., it then took longer before the gaze direction moved off-path). Again, no such effect was found if the gaze direction was off-path. This resulted in the proportion of on-path glances being highest when the cognitive demand from the tasks was highest.

Discussion

The increased proportion of on-path fixations is in line with the gaze concentration effect which is well-established for longer periods of driving on highways and other larger roads. But while an increased proportion of on-path fixations appears safety beneficial in such environments, it is most likely not the case in environments such as the currently studied, which have relevant information in off-path locations.

The different effects of cognitive load on on-path and off-path fixations and glances demonstrate the need to better understand the interplay between the driving task and the secondary task.

5. Discussion

5.1. Response times during cognitive activities

The results in Paper I show that cognitive load has different effects on response times in the DRT and in an unexpected critical lead vehicle braking scenario. While DRT response times increased with increased cognitive load, which is in line with numerous previous studies (Bruyas & Dumont, 2013; Conti et al., 2012; Engström, Larsson et al., 2013; Harbluk et al., 2013; Mantzke & Keinath, 2015; Merat & Jamson, 2008; Patten et al., 2004; Törnros & Bolling, 2005), brake response times in the lead vehicle braking scenario were unaffected by cognitive load.

The Paper I finding appears to be in line with the cognitive control hypothesis (Engström et al., 2017), discussed in Chapter 2.1.1. That is, the increased response times in the DRT can be explained by the need of cognitive control for generating a response, due to the novelty of the task. The lead vehicle braking scenario in Paper I was however implemented so that visible looming of the lead vehicle appeared as soon as the lead vehicle started braking and the drivers thus presumably responded automatically to the looming cues. Cognitive load did therefore not have an effect on response times.

The results in Paper I clearly demonstrate that effects of cognitive tasks seen in cognitively controlled response tasks, such as the DRT, should not be generalized to critical situations in which drivers can respond to visual looming. Statements such as “Drivers who are [cognitively] distracted ... are slower to take evasive action when it is needed” (Strayer & Fisher, 2016) do thus not appear to be warranted. Response times in situations where cognitive control is involved are however likely to increase, just as the DRT response times. Such a situation could for example be when negotiating with multiple other road users in a complex intersection, where fast decisions are necessary. It can also be when a potential conflict can be predicted using cues in the traffic environment, such as in the studies by Baumann et al. (2008) and Muttart et al. (2007). Apart from response time effects, the cognitive control hypothesis predicts deteriorated performance in other situations where cognitive control is required for an appropriate, although not necessarily fast, response. This is discussed further in Chapter 5.3.

5.2. Visual behaviour during cognitive activities

The general effect of cognitive load on drivers' visual behaviour that has been repeatedly found on primarily highways and main roads, namely an increased amount of glances towards the future path (Harbluk et al., 2007; Recarte & Nunes, 2000, 2003; Reimer et al., 2013, 2012; Reimer, 2009; Victor et al., 2005; Wang et al., 2014), was also seen in the intersection and hidden exit scenarios in Paper II. The drivers' visual behaviour was however not only studied at the aggregated level, but also at a deeper level with a higher temporal resolution. It was then found that in relation to the traffic environment, the timing of the glances towards relevant areas in off-path locations was unaffected by cognitive load. In other words, the gaze patterns in relation to the traffic environment were unaffected by cognitive load in terms of timing, but changed so that the proportion of on-path fixations was larger. Rather than cognitive load causing a delay in glances towards relevant off-path locations (as speculated by Lehtonen et al., 2012), it thus appeared that some off-path glances were missed. The risk of such "absent glances" did not appear to depend on the traffic environment and were not compensated for later on.

An interesting finding in Paper II was that the effect of cognitive load on the visual behaviour depended on gaze direction and the demand fluctuations in the cognitive task. If the gaze direction was on-path when the demand in the cognitive task increased, it took longer before it changed to an off-path gaze direction compared to if there was no cognitive task. However, if the gaze direction was off-path when the demand in the cognitive task increased, no difference was seen in the time it took before it changed to an on-path gaze direction compared to if there was no task. That is, the increase in cognitive load caused a gaze freezing effect in on-path glances only, but left off-path glances unaffected. This resulted in the proportion of on-path fixations being largest when the demand from the cognitive task was highest.

One way to try to interpret the results is again in terms of the cognitive control hypothesis (Engström et al., 2017). If we assume that drivers automatically direct their gaze towards the future path (because that is the most frequent and consistent gaze direction, or because it is the gaze direction required for the most frequent and consistent task, the lane keeping), then eyes-on-path becomes the automatic default gaze location. It would follow that moving the gaze to an off-path location requires cognitive control (as has been speculated by Lehtonen et al., 2012). That is, drivers that have an on-path gaze direction during increased cognitive load are less likely

to switch to an off-path gaze direction since that would require cognitive control. Drivers that on the other hand have an off-path gaze direction during increased cognitive load would switch back to the default on-path gaze direction automatically, and the cognitive load would hence not disrupt that gaze switch. Thus gaze concentration can be viewed as an automatic behaviour reverting gaze to the default location. This default location is likely built up over time through successful employment of neural pathways (Cohen et al., 1990) used during the extensively practiced lane keeping task.

An alternative interpretation could be that if one instead assumes that cognitive load affects all glances equally, regardless of gaze direction, and that gaze freezing is a sign of cognitive engagement in a secondary task, then the gaze freezing effect seen only in on-path glances could be a sign of task prioritization. That is, the drivers wait with engaging cognitively in the secondary task until they have their eyes on the road.

5.3. Implications for traffic safety

The overall aim of this PhD project is to increase the understanding of how cognitive activities affect car driver's abilities and behaviours from a traffic safety perspective. The intent is that this work contributes to a more detailed understanding of these complicated relationships and add to a nuanced discussion, rather than tries to give absolute answers in terms of general safety consequences.

The results in both Paper I and Paper II demonstrate the necessity of placing the cognitive activity in a context before trying to draw conclusions of its effects on traffic safety. The decreased risk of rear-end collisions during cell phone conversations (Victor et al., 2015) can possibly be explained by the increased proportion of on-path fixations in combination with unaffected response times in unexpected lead vehicle braking situations. The decreased proportion of fixations towards safety relevant objects in off-path locations is however likely to reduce the driver's situation awareness and could make him/her less prepared in case a potential threat turns into an actual threat. More generally, cognitive load seems to affect non-automatic behaviours.

The cognitive control hypothesis (Engström et al., 2017), if further supported, appears useful for increasing the understanding of how and when cognitive activities affect driver behaviours and traffic safety. According to the hypothesis, cognitive activities should increase the risk of accidents only when there is no suitable automatized behaviour for the driver to fall back upon (Engström et al., 2017). The effect on traffic safety hence depends both

on the driver's experience (what behaviours s/he has automatized) and the specific situation. For example, cognitive control is required to adapt to changes in otherwise extensively practiced tasks, making changes in routine situations likely to be negatively affected by cognitive load. This could be seen in a study by Cooper et al. (2003) in which the average time gap when drivers accepted to make a left turn on a test track was studied. When the road was dry, there was no difference in gap acceptance between drivers performing a cognitive task and not. However, when the road was wet, only the drivers not doing a cognitive task adapted to the changed conditions by increasing their gap acceptance time. The cognitively loaded drivers kept the same gap acceptance time, which presumably represented their automatized gap acceptance behaviour.

The main difficulty in proving and using the cognitive control hypothesis is that there is today no validated method to determine the level of cognitive control required by a driving task (or a secondary task).

The results in Paper II call for further research in order to understand the interaction between cognitive tasks and the task of driving. For example, because the drivers did not appear to recoup "absent glances" to off-path locations, the timing between cognitive task peaks and intended gaze shifts appears important from a traffic safety perspective. That is, the probability that a driver fails to scan an important area might depend on the timing between intended gaze shifts to that area and peaks in cognitive task load. Just as the timing between off-path glances and lead vehicle braking events are decisive of the risk of rear-end collisions (Victor et al., 2015), so could the timing between cognitive task engagement and intended gaze shifts be decisive of the risk of missing relevant information in off-path locations.

6. Conclusions

Does cognitive load affect drivers' response times in an unexpected, critical lead vehicle braking scenario in the same way as in the artificial Detection Response Task (DRT)?

Paper I shows that while DRT response times increased with increased cognitive load, the response times to a braking lead vehicle were unaffected. The results can be understood in terms of the cognitive control hypothesis. The hypothesis suggests that DRT response times are affected because the DRT is a novel task to the participants and hence requires cognitive control. The drivers in the lead vehicle braking scenario however respond automatically to the visual looming cues and response times are therefore unaffected by cognitive load.

Are the general effects of cognitive load on drivers' visual behaviour found on highways and main roads similar in traffic scenarios with relevant visual information in off-path locations, namely intersections and hidden exits?

Paper II shows that the increased amount of glances towards the future path typically found on highways and main roads were also seen in a rural intersection scenario and a hidden exit scenario with relevant visual information in off-path locations. Although drivers still adapted their visual behaviour to the traffic environment by expanding their gaze pattern (looking towards off-path locations) in the intersection and hidden exit scenarios, they did so to a lesser extent when cognitively loaded.

How does the time course of driver visual behaviour respond to a cognitive task and to relevant information in off-path locations in the traffic environment?

Paper II shows that although the proportion of off-path fixations decreased during cognitive load, drivers still had the same gaze expansion pattern with respect to timing in relation to the traffic environment. It was also found that the proportion of on-path fixations was largest when the demand from the cognitive task was highest. Glances that were on-path were prolonged in time (stayed on-path for a longer time) when the demand from the cognitive task increased, while glances that were off-path were not prolonged.

Implications

The results presented in this thesis demonstrate how there is not one general effect of cognitive tasks on driver behaviours and traffic safety. Cognitive activities thus has to be put into a context in order to be understood and

interpreted from a traffic safety perspective. Effects of cognitive tasks seen in cognitively controlled response tasks, such as the DRT, should not be generalized to critical situations where drivers can respond to visual looming. Neither should safety implications of gaze concentration be assumed without taking the traffic scenario into consideration. That is, whether gaze concentration impacts crash outcomes may highly depend on the type of crash scenario and degree of involvement of cognitive control needed to direct gaze off-path.

The finding that cognitive tasks affected on- and off-path fixations and glances differently calls for further exploration. It suggests that there is not a unidirectional and uniform effect of cognitive activities on driver behaviour. Increased understanding of the interplay between the driving task and the cognitive task could possibly help in further understanding effects of cognitive activities on traffic safety.

7. Future work

The future work should help fulfil the overall aim of this PhD project, namely to increase the understanding of how cognitive activities affect car driver's abilities and behaviours from a traffic safety perspective. The work will continue exploring the interaction between cognitive tasks and the task of driving. It will also focus on increasing interpretability of results and allowing for more naturalistic study designs by examining the use of physiological measures for assessing both cognitive activity and other driver states.

The following work will be undertaken:

- The use of physiological measures (e.g. electrocardiography, pupillometry and respiration) to assess driver states and cognitive activity will be explored. Driver states, e.g. sleepiness, emotions and stress, impact driver behaviour (Chan & Singhal, 2015; Philip et al., 2005) and how drivers deal with cognitive tasks (Horrey, Lesch, Garabet, Simmons, & Maikala, 2017; Oken, Salinsky, & Elsas, 2006). They are therefore important to monitor in experimental studies where they might interfere with the aim of the study, and also to explicitly study in order to increase the understanding of their impact on cognitive activity and driver behaviour. Unobtrusive and continuous measuring of cognitive activity is needed to allow for more naturalistic study designs. Physiological signals are selected because they have been shown to correlate with various driver states (Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2014; Brookhuis & de Waard, 2010; Sharma & Gedeon, 2012) and have the possibility to enable unobtrusive and continuous measuring. The work will focus on how the different measures can complement each other and together can give a driver state assessment.
- The use of electroencephalography (EEG) in driving studies on cognitive distraction will be explored. EEG has very high time resolution and can potentially enable more direct measurements of cognitive activities. It is however a very artefact-prone signal, difficult to measure in applied settings such as driving (Nilsson et al., 2017; Strayer et al., 2013). Therefore, EEG measures which work in a driving context and can help in the exploration of the interaction between the driving task and a cognitive task will be pursued and explored.

- The interplay between the driving task and the cognitive task will be studied further with the hope of increasing the knowledge of why and when cognitive tasks causes problems for car drivers.

References

- Ahlstrom, C., Victor, T., Wege, C. & Steinmetz, E. (2012). Processing of eye/head-tracking data in large-scale naturalistic driving data sets. *IEEE Transactions on Intelligent Transportation Systems*, 13(2), 553–564.
- Alm, H. & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident; analysis and prevention*, 27(5), 707–15.
- Angell, L., Auflick, J., Austria, P., Kochhar, D., Tijerina, L., Biever, W., Diptiman, T., et al. (2006). *Driver workload metrics Task 2 Final Report*. (No. DOT HS 810 635). Washington, DC: Department of Transportation, National Highway Traffic Safety Administration.
- Baumann, M. R., Petzoldt, T., Groenewoud, C., Hogema, J. & Krems, J. F. (2008). The effect of cognitive tasks on predicting events in traffic. In Brusque, Corinne (Ed.), *Proceedings of the European Conference on Human Centred Design for Intelligent Transport Systems* (pp. 3–11).
- Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D. & Babiloni, F. (2014). Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue and drowsiness. *Neuroscience & Biobehavioral Reviews*, 44, 58–75. Elsevier.
- Botvinick, M. M. & Cohen, J. D. (2014). The computational and neural basis of cognitive control: charted territory and new frontiers. *Cognitive science*, 38(6), 1249–1285. Wiley Online Library.
- Brookhuis, K. A. & de Waard, D. (2010). Monitoring drivers' mental workload in driving simulators using physiological measures. *Accident Analysis & Prevention*, 42(3), 898–903. Elsevier.
- Bruyas, M.-P. & Dumont, L. (2013). Sensitivity of Detection Response Task (DRT) to the driving demand and task difficulty. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 64–70).
- Caird, J. K., Johnston, K. A., Willness, C. R., Asbridge, M. & Steel, P. (2014). A meta-analysis of the effects of texting on driving. *Accident Analysis & Prevention*, 71, 311–318. Elsevier.

- Caird, J. K., Willness, C. R., Steel, P. & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis & Prevention*, 40(4), 1282–93.
- Chan, M. & Singhal, A. (2015). Emotion matters: Implications for distracted driving. *Safety science*, 72, 302–309. Elsevier.
- Cohen, J. D., Dunbar, K. & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological review*, 97(3), 332–61.
- Conti, A. S., Dlugosch, C., Vilimek, R., Keinath, A. & Bengler, K. (2012). An assessment of cognitive workload using detection response tasks. In N. A. Stanton (Ed.), *Advances in human aspects of road and rail transport* (pp. 735–743). CRC Press.
- Cooper, P. J., Zheng, Y., Richard, C., Vavrik, J., Heinrichs, B. & Siegmund, G. (2003). The impact of hands-free message reception/response on driving task performance. *Accident Analysis & Prevention*, 35(1), 23–35.
- Dingus, T. A., Guo, F., Lee, S., Antin, J. F., Perez, M., Buchanan-King, M. & Hankey, J. (2016). Driver crash risk factors and prevalence evaluation using naturalistic driving data. *Proceedings of the National Academy of Sciences*, 113(10), 2636–2641. National Acad Sciences.
- Drews, F. A., Yazdani, H., Godfrey, C. N., Cooper, J. M. & Strayer, D. L. (2009). Text messaging during simulated driving. *Human factors*, 51(5), 762–70.
- Engström, J., Victor, T. & Markkula, G. (2013). Attention Selection and Multitasking in Everyday Driving: A Conceptual Model. In Reagan, Michael and Lee, John D. and Victor, Trent W. (Ed.), *Driver Distraction and Inattention: Advances in Research and Countermeasures* (pp. 27–54). ASHGATE.
- Engström, J. (2010). Scenario criticality determines the effects of working memory load on brake response time. In J. Krems and T. Petzoldt and M. Henning (Ed.), *Proceedings of the European Conference on Human Centred Design for Intelligent Transport Systems (HUMANIST)*, Lyon, France (pp. 25–36).
- Engström, J., Aust, M. L. & Viström, M. (2010). Effects of working memory load and repeated scenario exposure on emergency braking

- performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 52(5), 551–559.
- Engström, J., Larsson, P. & Larsson, C. (2013). Comparison of static and driving simulator venues for the tactile detection response task. *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 369–375).
- Engström, J., Markkula, G., Victor, T. & Merat, N. (2017). Effects of Cognitive Load on Driving Performance: The Cognitive Control Hypothesis. *Human factors*, 59(5), 734–764.
- Engström, J., Monk, C., Hanowski, R., Horrey, W., Lee, J., McGehee, D., Regan, M., et al. (2013). *A conceptual framework and taxonomy for understanding and categorizing driver inattention*. US-EU ITS Cooperation, Driver Distraction and HMI Working Group. Retrieved from <https://ec.europa.eu/digital-single-market/en/news/us-eu-inattention-taxonomy-report>
- Fisher, D. L. (2015). Cognitive Distraction in the Wild: Next Steps—Addressing a Not-So-Humdrum Conundrum. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57(8), 1331–1333.
- Fitch, G. M., Soccolich, S. A., Guo, F., McClafferty, J., Fang, Y., Olson, R. L., Perez, M. A., et al. (2013). *The impact of hand-held and hands-free cell phone use on driving performance and safety-critical event risk*. (DOT HS 811 757). Washington, DC: Department of Transportation, National Highway Traffic Safety Administration.
- Hancock, P. A. & Sawyer, B. D. (2015). Judging Thieves of Attention: Commentary on “Assessing Cognitive Distraction in the Automobile,” by Strayer, Turrill, Cooper, Coleman, Medeiros-Ward, and Biondi (2015). *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57(8), 1339–1342.
- Harbluk, J. L., Burns, P. C., Hernandez, S., Tam, J. & Glazduri, V. (2013). Detection response tasks: Using remote, headmounted and Tactile signals to assess cognitive demand while driving. *Proc. 7th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design* (pp. 78–84).

- Harbluk, J. L., Noy, Y. I., Trbovich, P. L. & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis & Prevention*, 39(2), 372–379.
- Hickman, J. S., Hanowski, R. J. & Bocanegra, J. (2010). *Distraction in commercial trucks and buses: Assessing prevalence and risk in conjunction with crashes and near-crashes*. (Report No. FMCSA-RRR-10-049). Washington, DC: Federal Motor Carrier Administration.
- Horrey, W. J., Lesch, M. F., Garabet, A., Simmons, L. & Maikala, R. (2017). Distraction and task engagement: how interesting and boring information impact driving performance and subjective and physiological responses. *Applied ergonomics*, 58, 342–348.
- International Organization for Standardization, ISO. (2016). *Road Vehicles - Transport information and control systems -Detection-response task (DRT) for assessing attentional effects of cognitive load in driving*. ISO 17488:2016, IDT
- Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D. & Ramsey, D. J. (2006). *The impact of driver inattention on near-crash/crash risk: An analysis using the 100-car naturalistic driving study data*. (No. DOT HS 810 59). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
- Klauer, S. G., Guo, F., Sudweeks, J. & Dingus, T. A. (2010). *An analysis of driver inattention using a case-crossover approach on 100-car data: Final report*. (No. DOT HS-811-334). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
- Lee, J. D., Caven, B., Haake, S. & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effect of speech-based e-mail on drivers' attention to the roadway. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 43(4), 631–640.
- Lehtonen, E., Lappi, O. & Summala, H. (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation research part F: traffic psychology and behaviour*, 15(3), 369–377.
- Lin, J. Y., Franconeri, S. & Enns, J. T. (2008). Objects on a collision path with the observer demand attention. *Psychological science*, 19(7), 686–92.

- Mantzke, O. & Keinath, A. (2015). Relating the Detection Response Task to Critical Events-Consequences of high Cognitive Workload to Brake Reaction Times. *Procedia Manufacturing*, 3, 2381–2386.
- Markkula, G., Engström, J., Lodin, J., Bårgman, J. & Victor, T. (2016). A farewell to brake reaction times? Kinematics-dependent brake response in naturalistic rear-end emergencies. *Accident Analysis & Prevention*, 95, 209–226.
- Merat, N. & Jamson, A. H. (2008). The effect of stimulus modality on signal detection: implications for assessing the safety of in-vehicle technology. *Human factors: The Journal of the Human Factors and Ergonomics Society*, 50(1), 145–58.
- Miller, E. K. & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Reviews of Neuroscience*, 24, 167–202.
- Muttart, J., Fisher, D., Knodler, M. & Pollatsek, A. (2007). Driving without a clue: Evaluation of driver simulator performance during hands-free cell phone operation in a work zone. *Transportation Research Record: Journal of the Transportation Research Board*, 2018, 9–14.
- Náñez, J. (1988). Perception of impending collision in 3-to 6-week-old human infants. *Infant Behavior and Development*, 11(4), 447–463.
- Nilsson, E., Ahlström, C., Barua, S., Fors, C., Lindén, P., Svanberg, B., Begum, S., et al. (2017). Vehicle Driver Monitoring: sleepiness and cognitive load. (Report No. 937A). Linköping, Sweden: Statens väg-och transportforskningsinstitut.
- Oken, B. S., Salinsky, M. C. & Elsas, S. M. (2006). Vigilance, alertness, or sustained attention: physiological basis and measurement. *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, 117(9), 1885–901.
- Oliva, D., Medan, V. & Tomsic, D. (2007). Escape behavior and neuronal responses to looming stimuli in the crab *Chasmagnathus granulatus* (Decapoda: Grapsidae). *Journal of Experimental Biology*, 210(5), 865–880.
- Olson, R. L., Hanowski, R. J., Hickman, J. S. & Bocanegra, J. L. (2009). *Driver distraction in commercial vehicle operations*. (No. FMCSA-RRR-09-042). Washington, DC: Department of Transportation, Federal Motor Carrier Safety Administration.

- Patten, C. J. D., Kircher, A., Östlund, J. & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis & Prevention*, 36(3), 341–350.
- Philip, P., Sagaspe, P., Moore, N., Taillard, J., Charles, A., Guilleminault, C. & Bioulac, B. (2005). Fatigue, sleep restriction and driving performance. *Accident Analysis & Prevention*, 37(3), 473–478.
- Recarte, M. A. & Nunes, L. M. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of experimental psychology. Applied*, 6(1), 31–43.
- Recarte, M. A. & Nunes, L. M. (2003). Mental workload while driving: effects on visual search, discrimination, and decision making. *Journal of experimental psychology. Applied*, 9(2), 119–37.
- Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. *Transportation Research Record: Journal of the Transportation Research Board*, (2138), 13–19.
- Reimer, B., Mehler, B., Dobres, J. & Coughlin, J. (2013). The effects of a production level "voice-command" interface on driver behavior: summary findings on reported workload, physiology, visual attention, and driving performance. (Technical Report 2013-17A). Cambridge, MA: Massachusetts Institute of Technology, AgeLab.
- Reimer, B., Mehler, B., Wang, Y. & Coughlin, J. F. (2012). A field study on the impact of variations in short-term memory demands on drivers' visual attention and driving performance across three age groups. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 54(3), 454–468.
- Salvucci, D. D. & Beltowska, J. (2008). Effects of memory rehearsal on driver performance: experiment and theoretical account. *Human factors*, 50(5), 834–44.
- Schiff, W., Caviness, J. A. & Gibson, J. J. (1962). Persistent fear responses in rhesus monkeys to the optical stimulus of "looming." *Science*, 136(3520), 982–983.
- Schneider, W. & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review*, 84(1), 1 – 66.

- Sharma, N. & Gedeon, T. (2012). Objective measures, sensors and computational techniques for stress recognition and classification: a survey. *Computer methods and programs in biomedicine*, 108(3), 1287–301.
- Shiffrin, R. M. & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological review*, 84(2), 127.
- Shinar, D. (2015). Cognitive Workload ≠ Crash Risk: Rejoinder to Study by Strayer et al. (2015). *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57(8), 1328–1330.
- Strayer, D., Cooper, J., Turrill, J., Coleman, J. & Hopman, R. (2015). The smartphone and the driver's cognitive workload: A comparison of Apple, Google, and Microsoft's intelligent personal assistants. *AAA Foundation for Traffic Safety*.
- Strayer, D. L., Cooper, J. M., Turrill, J., Coleman, J., Medeiros-Ward, N. & Biondi, F. (2013). Measuring cognitive distraction in the automobile. *AAA Foundation for Traffic Safety*.
- Strayer, D. L., Drews, F. A. & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of experimental psychology: Applied*, 9(1), 23–32.
- Strayer, D. L. & Fisher, D. L. (2016). SPIDER: A Framework for Understanding Driver Distraction. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 5–12.
- Strayer, D. L., Turrill, J., Cooper, J. M., Coleman, J. R., Medeiros-Ward, N. & Biondi, F. (2015). Assessing cognitive distraction in the automobile. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57(8), 1300–1324.
- Summala, H. (2007). Towards understanding motivational and emotional factors in driver behaviour: Comfort through satisficing. In *Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems* (pp. 189–207).
- Törnros, J. E. B. & Bolling, A. K. (2005). Mobile phone use-effects of handheld and handsfree phones on driving performance. *Accident Analysis & Prevention*, 37(5), 902–909.

- U.S. Department of Transportation, National Highway Traffic Safety Administration. (2013). *Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices* (Docket No. NHTSA-2010-0053). Retrieved from <https://www.gpo.gov/fdsys/pkg/FR-2013-04-26/pdf/2013-09883.pdf>.
- Victor, T., Dozza, M., Bärghman, J., Boda, C.-N., Engström, J., Flannagan, C., Lee, J. D., et al. (2015). *Analysis of naturalistic driving study data: Safer glances, driver inattention, and crash risk*. (SHRP 2 Safety Project S08A). Washington, DC: Transportation Research Board.
- Victor, T. W., Harbluk, J. L. & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2), 167–190.
- Wang, Y., Reimer, B., Dobres, J. & Mehler, B. (2014). The sensitivity of different methodologies for characterizing drivers' gaze concentration under increased cognitive demand. *Transportation research part F: traffic psychology and behaviour*, 26, 227–237.
- Young, R. A. (2015). Driver Compensation Impairment or Improvement? *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 57(8), 1334–1338.